

Ultrasonic Time of Flight Diffraction Technique for Weld Defects: A Review

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Abstract: To achieve the quality and safety in industrial applications, the damaged products must be detected. To do that NDT is used. In NDT, Ultrasonic Time-of-Flight Diffraction is a well-known technique for detecting the size and location of the defects. Nowadays the Time of Flight Diffraction (ToFD) is used for inspecting the materials during production than that of radiography and other ultrasonic NDT procedures. ToFD technique can be used into many different ways. This study gives a review of various ultrasonic ToFD techniques for welding defects and aims at the usage of it.

Keywords: i-ToFD, NDT, s-ToFD, ToFD, UT, weld, weld defects

INTRODUCTION

The concept of detecting flaws without destroying the material is called Non-Destructive Testing. Without making any damage, the characteristics of the component, material, or system can also be examined using this NDT techniques. NDT can save both money and time in their applications. Basically the highly-valuable technique NDT comprises of:

- Non-Destructive Examination
- Nondestructive Inspection
- Nondestructive Evaluation

It is a tool in engineering, medicine and art (Wikipedia, 2012).

Various Non-Destructive Testing and Evaluation methods are Magnetic-Particle testing, Liquid Penetrant testing, Eddy-current testing, Visual testing, Radiographic testing, Ultrasonic testing, Thermographic testing, Electromagnetic testing, Low coherence interferometry testing and Optical testing methods. These methods are used to detect and evaluate internal discontinuities or leaks in a system. One of the areas wherein NDE is frequently used is Flaw Detection. It is in great demand in many industrial applications. Welding is a process of joining two materials using metals and thermoplastic through localized coalescence resulting from a suitable combination of pressure, temperature and metallurgical conditions. Based on the combination of pressure and

temperature, i.e., from a high temperature with no pressure to a low temperature with high pressure, a grand range of welding processes have been developed. Based on the energy sources, welding processes are basically divided into three types and they are Arc welding, MIG welding and TIC welding.

In industrial activities such as manufacturing, weld is used to join more than one metal surfaces or pieces. Since these weld connections may have fatigue and loads during the lifetime of the product, there is a chance that they may fail if it is not created properly (Wikipedia, 2012). To weld, the energy sources used for welding may be a gas flame, an electric arc, a laser, an electron beam, friction and ultrasound. Crack, Slag, Undercut, Porosity, LF, LP, Overlap, Excess Convexity, Excess Concavity, Excess weld Reinforcement and etc., are known as defects of weld. The typical welding defects could create a structure to break or a pipeline to rupture.

The refined weld or welded material must be inspected for weld defects. These are all the important factors to check whether a welding work is to be accepted or rejected based on which, the quality of the weld is to be determined. Welds may be tested by NDT techniques such as industrial radiography or industrial CT scanning using X-rays or γ -rays, UT, etc.,. In a proper weld, these tests would indicate a lack of cracks in the radiograph, show clear passage of sound through the weld and back, or indicate a clear surface without penetrant captured in cracks (Absolute, 2011).

Vibrations of Sound waves are characterized by their frequencies. Based on their frequencies the sound

wave is divided into three. The frequencies of sound waves which are less than 20 Hz are known as Infrasound or Infrasonic waves. If the frequency lies between 20 Hz to 20 KHz then the sound wave is called Audible wave. Otherwise, the sound wave is called Ultrasound or Ultrasonic wave. Now we can discuss about Ultrasonic Testing and then ToFD for detecting flaws.

Introduction to ultrasonic testing: In Ultrasonic Testing, very short ultrasonic pulse-waves with center frequencies ranging from 0.1 to 15 MHz and rarely upto 50 MHz are launched into materials to detect interior flaws or to find the characteristics of materials. It is used to find the thickness of the test material. Ultrasonic testing is done on steel, other metals and alloys, concrete, wood and composites with less resolution. It is a form of NDT used in many industries such as aeronautic, automotive and other sectors also.

If there is a change in test material, then the ultrasonic waves will be reflected from the material. This principle is used in NDT. Since the flaws can be detected without destroying the material, It is called as NDT. In UT, an ultrasound transducer connected to an instrument is launched over the material being inspected. The transducer is separated from the material by a couplant. To receive the ultrasound waveform, two methods namely Reflection and Attenuation are used. In Pulse-Echo mode or Reflection mode, the transducer performs both the sending and the receiving of the pulsed waves as the "sound" is reflected back to the device (Wikipedia, 2012). Reflected ultrasound comes from an interface, such as the back wall of the material or from a defect within the material. The diagnostic machine displays these results in the form of a signal with amplitude representing the intensity of the reflection and the distance, representing the arrival time of the reflection (Wikipedia, 2012). In Attenuation (or through-transmission) mode, a transmitter sends ultrasound through one surface and a separate receiver detects the amount that has reached it on another surface after traveling through the medium. Imperfections or other conditions in the space between the transmitter and receiver reduce the amount of sound transmitted, thus revealing their presence (Wikipedia, 2012).

The couplant is used to increase the efficiency of the process by reducing the losses in the ultrasonic wave energy due to separation between the surfaces (EESL, 2011; Wikipedia, 2012). The NDT, UT and weld were discussed in Wikipedia (2012), EESL (2011)

and Absolute (2011). ART, EMAT, LUT, IRIS, PA, ToFD (s-ToFD, I-ToFD) are known as Ultrasonic techniques. Out of these Ultrasonic techniques, ToFD is one of the most widely used ultrasonic techniques for detecting flaws. Now we can discuss about the conventional ToFD, s-ToFD, etc., and its usage in the field of Flaw Detection.

METHODOLOGY

Time of flight diffraction technique: Applying ToFD to Ultrasonic Flaw Detection seems to be a promising area. We discuss the various ToFD techniques in this section. It was first described by Silk and used to detect, size & to locate the defects.

ToFD method: If an ultrasonic wave is incident on a defect, the wave is reflected, transmitted and also diffracted at the edges of the crack. The diffracted energy spreads over a wide angle and can be picked up from almost anywhere along the surface of the structure. The defect detection method based on the measurements of time difference between diffracted signals from the extremities of a defect is called ToFD technique. Diffraction takes place in space and its reception takes place in time. Hence it is named as the time of flight diffraction. ToFD does not depend on the orientation and surface features of the discontinuity. And it does not depend on the amplitude of the diffracted echo. Ultrasonic ToFD signals and the basic principle of ToFD have been illustrated in Fig. 1a, b, respectively.

Here,

- 1 : Lateral wave traveling just under the surface
- 2, 3 : Diffracted signal from top and bottom of the defect
- 4 : Back Wall (BW) echo i.e., Reflected echo
- L : Defect Size
- D : Defect Depth

D and L are obtained by the following Equations, (Baskaran *et al.*, 2006a):

$$D = \frac{\sqrt{v_L^2 t_1^2 - S^2}}{2} \quad (1)$$

- v_L : Longitudinal wave velocity inside the material
- S : Distance between the probes
- t_1, t_2 : Transit time of longitudinal diffracted echo from top and bottom of the defect

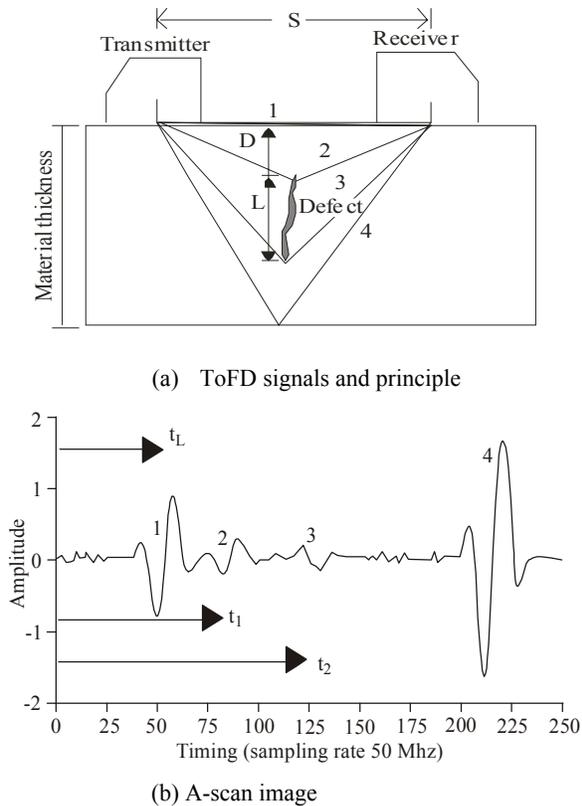


Fig. 1: Conventional ToFD technique-different signals at the receiver are shown in the A-scan image

$$L = \frac{1}{2} \sqrt{v_L^2 t_1^2 - S^2} - D \quad (2)$$

Flaw depth is to be calculated by the time delay between the Lateral wave and the longitudinal wave scattered by the tip.

Advantages of ToFD: Inspection Speed of ToFD is high. And it has high accurate defect sizing. i.e., when compared to conventional Ultrasonic and Radiography, the most important advantage of ToFD is a high POD, virtually independent on it defect orientation (SciVerse, 2012) i.e., low rate of false indication. And it is easy to use. It can be set up and operated quickly. Analysis can be performed immediately from the digital images and data are available for additional post test reviews (Tie and Dazhao, 2008). The authors (Subbaratnam *et al.*, 2006b) proposed that ToFD has faster scanning times and used for quantitative characterization with better accuracies.

Ultrasonic one-skip ToFD: In Ultrasonic ToFD method using longitudinal wave, the Shear wave is generated due to the MODE CONVERSION. It is not

so easy to detect flaws near the surface (<10 mm from the surface). Since flaw indications are hidden in the La Wave. Therefore, to detect flaws near the surface, 1Skip ToFD method and Signal processing used. i.e., 1Skip ToFD method detects diffraction waves from flaws near the surface after reflection at the back-wall. "When there are flaws near the surface, the difference of beam path length between the lateral wave & scattered wave from the flaw tip becomes small, it is hard to differentiate these waves." Hence, Ultrasonic 1Skip ToFD method used to obtain an indication of surface flaws with less influence of Lateral waves. In case of the One-Skip ToFD method, the longitudinal wave is reflected at the back-wall first, and then some longitudinal components go forward toward the flaw. Coincidentally, shear components are generated at the reflection. It is required that longitudinal components to set the test condition so as not to be influenced by the shear components. To obtain a flaw image near the surface without interference from shear components:

Distance between the sensors $\geq 4 * \text{plate thickness}$

When an angle of refraction increases, the distance between sensors increases and attenuation also increases. When appropriate conditions are chosen, One-Skip ToFD method and Conventional ToFD method have EQUAL ACCURACY (Nobukasu *et al.*, 2004). (Conditions: Distance between the Sensors = $4 * \text{plate thickness}$ & Angle of Refraction = 50 degree.)

Conventional ToFD (using longitudinal wave): Conventional ultrasonic technique uses the pulse transit time. PULSE TRANSIT TIME is used to locate and the echo amplitude to size the flaw. For accurate flaw sizing, the amplitude of the back reflected wave may not always be sufficient, since the amplitude of the reflected pulse may be influenced by many parameters other than the size of the reflector. Such parameters include the surface roughness, transparency and orientation of the defect. In order to ensure a more reliable defect sizing ultrasonic NDE technique, the ToFD method was developed. In general, amplitude of the Reflected Pulse may be influenced by the following parameters:

- Reflector Size
- Surface Roughness
- Transparency
- Orientation of the defect

To accurate Flaw size, the back reflected pulse's amplitude is not always enough, but it may require the

above parameters (Baskaran *et al.*, 2006a). This technique is limited to THICK (thickness >15 mm) sections & thickness <5 mm from the scanning surface. Near Surface Defects overestimated using it.

i.e., ToFD inspection applies two ultrasonic probes on either side of the weld as pitch-catch. For covering the complete weld volume and heat affected zone in one scan, the transmitter probe emits a wide angle beam. Thicker components (Thickness >50 mm) are subdivided in a number of depth zones. Possible defects diffract the sound beam at both the crack tips and the diffraction signals are retrieved from the receiver probe (SciVerse, 2012). i.e., it has the limitation during near surface inspection due to Signal SUPERPOSITION. In thin sections (with sensible surface breaking fatigue cracks), spacing between Back wall Longitudinal reflected signal and Lateral Signal is small. Therefore, the longitudinal diffracted echo is not detectable in B-scan image. But the temporal spacing of shear wave signal from the defect is to be observed and ToF to be measured from the B-scan image.

Disadvantages of conventional ToFD:

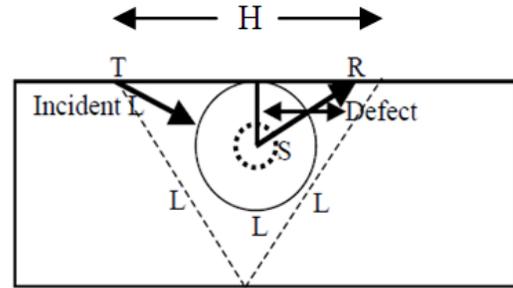
- Thick sections only
- Near surface defects were overestimated
- In order to identify the echoes and to get possible signal for analysis, it needs manual or automated articulation of the transducer (Jennifer *et al.*, 2006).

Shear wave ToFD: If an incident longitudinal wave front meets the defect, the wave diffracted as Longitudinal Diffracted Wave (L) and Shear Diffracted Wave (S):

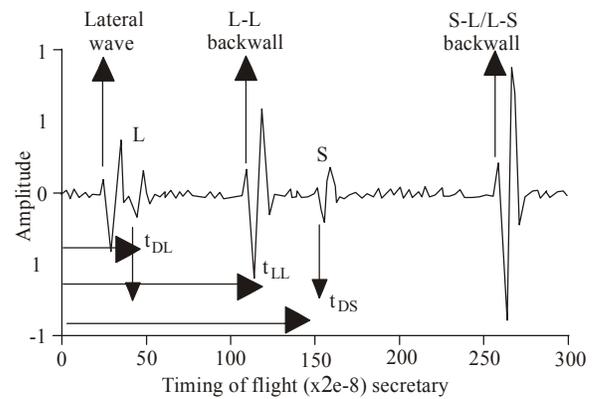
$$\text{Velocity of Shear Wave} = 1/2 * \text{Velocity of Longitudinal Wave}$$

Shear wave velocity is smaller. Hence L reaches the receiver first followed by S. S-ToFD uses the advantage of the slower velocity of the diffracted shear wave to improve the ToF measurements and consequently improve flaw sizing. Simulated results of surface crack and embedded crack of an Aluminium Sample (Length = 4 mm; Thick = 20 mm; Probe Frequency = 10 MHz) are given in Fig. 2 (Baskaran *et al.*, 2006b) and Fig. 3 (Baskaran *et al.*, 2006b).

where, L_t & S_t -L & S from top tip; L_b & S_b -L & S from bottom tip; Longitudinal-diffracted echo (L_t & L_b) always appear in between Lateral wave & L-L back wall echo. Though the diffraction coefficient of shear wave is less than the diffraction coefficient of



(a) Defect configuration



(b) A-scan image

Fig. 2: Longitudinal & shear wave diffraction for a surface crack in s-ToFD technique- different signals at the receiver are shown in the A-scan

longitudinal wave, Shear-wave diffracted echoes are detectable in case of thin and near-surface inspections (Baskaran *et al.*, 2006b).

Defect Depth D:

$$L = \sqrt{\frac{v_L^2 t_{sb}^2}{(n+1)^2} - S^2} \tag{3}$$

Defect Size or Length L:

$$L = \sqrt{\frac{v_L^2 t_{sb}^2}{(n+1)^2} - S^2 - D} \tag{4}$$

where,

- $n = v_L / v_S$; S-Shear wave Diffracted wave
- t_{st} -Arrival time of shear Diffracted signal from top of the defect
- t_{sb} -Arrival time of shear Diffracted signal from bottom of the defect
- L-Defect Size
- D-Defect Depth

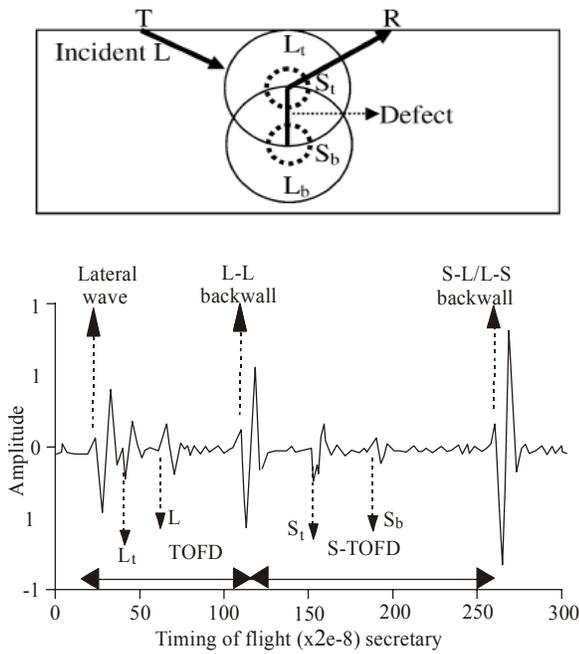


Fig. 3: Longitudinal and shear wave diffraction for an embedded crack in s-ToFD technique-different signals at the receiver are shown in the A-scan image

For getting shear-diffracted echo after longitudinal reflected echo, the probe separation is required. The minimum probe separation between transmitter and receiver is X. Here, H is thickness of the specimen surface and:

$$R = \frac{1}{4} \left(1 + \frac{v_L}{v_S} \right)^2 \quad (5)$$

Probe Separation X:

$$X > 2 \sqrt{\frac{H^2 - RL^2}{R-1}} \quad (6)$$

In defect tip identification, the choice of probe frequency plays an important role. Near-surface inspection is also possible using proper probe angles.

Advantage of S-ToFD: The longitudinal diffraction may superimpose. But the shear wave-diffracted echo from the top tip of the defect is to be clear in A-scan, gives accurate measurements of time of flight calculations (Baskaran *et al.*, 2006b).

Laser ToFD system: Laser Ultrasound is a non-contact measurement method used to realize the flexible system because both excitation & detection of the echo can be

made optically and scanning system can be designed compact. Laser is mainly used only for ultrasonic generation and other method such as Broad-band piezoelectric probe or EMAT. Since the directivity of laser ultrasound is broad, laser ultrasound is suitable for the ToFD method.

Laser ToFD system uses both longitudinal wave & Shear wave. Without knowing the SPECIMEN VELOCITY and PROBE DISTANCE previously, one can obtain accurate flaw depth. ToFD Lateral wave, flaw tip-diffracted wave, and mode converted shear wave at flaw tip is used for estimating the defect depth (Tie and Dazhao, 2008).

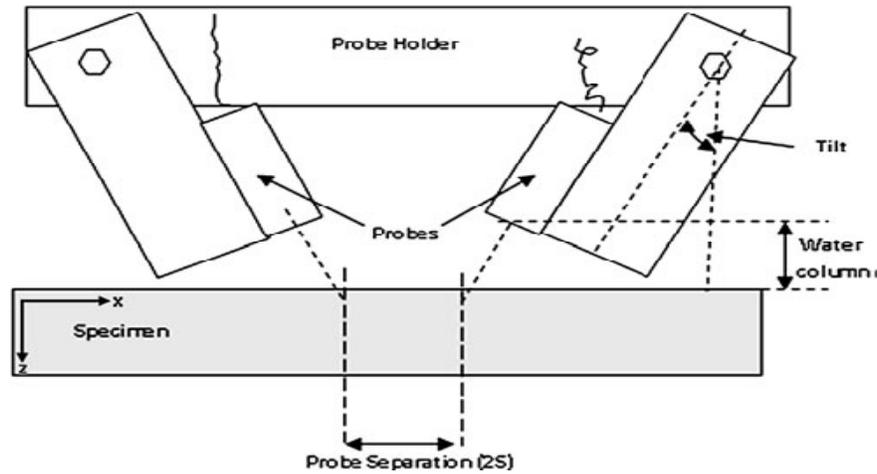
Immersion-ToFD: When the thickness of the specimen reduces, the echo signals will be merged together and it is very difficult to identify and size the discontinuity. Also, the size of conventional transducers limits the required probe separation. Limited success has been obtained internationally through the application of miniature probes and software for extending ToFD to lower thicknesses. Baskaran *et al.* (2006b) have tried to overcome the limitation of the merging of signals in thin sections by using miniature high frequency probes coupled with a digital signal processing technique called the Embedded Signal Identification Technique (Baskaran *et al.*, 2004) and with shear wave ToFD (Baskaran *et al.*, 2006b). In these cases, the minimum thickness that has been examined is 7 mm. i.e., the problem of thin section examination in the conventional ToFD is eliminated by i-ToFD. This new methodology has been proposed by Subbaratnam *et al.* (2011) and Subbaratnam *et al.* (2006a) that successfully extend the application of ToFD to thinner sections down to 3 mm. From the experimental study, (Subbaratnam *et al.*, 2006a) concluded to have best possible results the given things are to be considered:

- Probe angle is small
- Water path length is small
- Lower optimum frequency of the order of 5 MHz

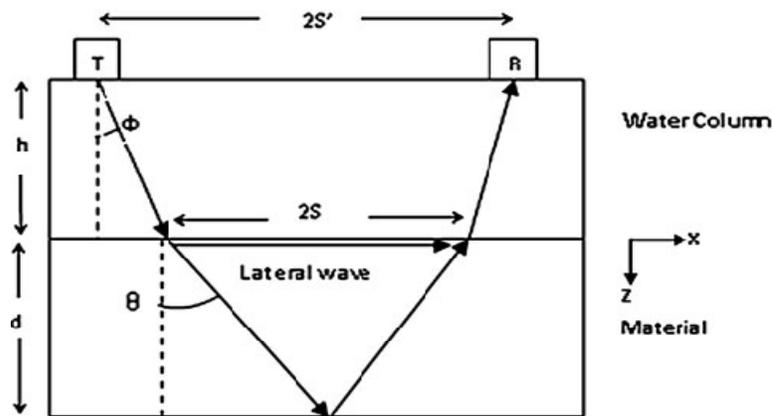
Immersion coupling provides a delay line, the necessary angles and probe separation making it possible to examine the thin components successfully.

where, h = vertical thickness of the water column, d = thickness of the material, ϕ = Wave propagation angle in water, θ = angle of refraction in material, $2S'$ = probe separation in water.

Immersion testing in ultrasonics is widely used for testing of materials. Some of the advantages of



(a) Schematic of the experimental setup



(b) Wave propagation

Fig. 4: Immersion ToFD (i-ToFD) (Subbaratnam *et al.*, 2011)

immersion ultrasonic testing include minimizing the dead zone, excellent coupling and the possibility of varied angles of incidence. Immersion helps in providing sufficient time delay, the necessary probe separation and the required angle of incidence. The time difference between lateral wave and back wall echoes can be increased by decreasing the beam angle in the material. This is achieved in immersion ToFD (i-ToFD) since the immersion probes can be tilted in water such that the desired angle is generated within the material by the principle of law of refraction. This is not possible in conventional ToFD since the conventional ToFD probes have fixed beam angles. Experimental setup and wave propagation of i-ToFD is given above in Fig. 4. All the side drilled holes in 5 mm thick specimen and notches in 3 mm thick specimen

were found by Subbaratnam *et al.* (2006a) easily by both longitudinal and shear wave modes with accuracy for sizing & depth detection. So, ToFD is used in many different ways to detect the defects.

RESULTS AND DISCUSSION

Initially, near surface inspections have been done by Nobukasu *et al.* (2004), Charlesworth and Hawker, (1984) using ToFD. But Nobukasu *et al.* (2004) achieved the near-surface ToFD inspection using one-skip ToFD method for an inspection thickness of 10 mm. And they found when the distance between sensors is about four times of the plate thickness and the angle of refraction is 50. Accuracy (Subbaratnam *et al.*, 2006a; Tie and Dazhao, 2008; SciVerse, 2012)

and sizing of defects (Silk, 1987; Sinclair *et al.*, 2010) using ToFD and the absolute time measurement in laser ToFD (Mihara *et al.*, 2004) discussed. The practical applicability of ToFD discussed in Zahran *et al.* (2002), Riahi *et al.* (2006), BOSSUAT *et al.* (2006), Kechida *et al.* (2008) and Muthumari *et al.* (2011). ToFD using ESID (Baskaran *et al.*, 2004) and different methods were discussed in Young-Fo *et al.* (2002), Baskaran *et al.*, (2007), Yonghong *et al.* (2008) and Yuwen *et al.* (2010). Manual ToFD (Nath *et al.*, 2010) and i-ToFD (Subbaratnam *et al.*, 2006a, 2011) were also discussed. Near surface (Charlesworth and Hawker, 1984; Nobukasu *et al.*, 2004; Baskaran *et al.*, 2006a, b), Bottom surface buried depth (Tie and Dazhao, 2008), deeper flaws (Tianlu *et al.*, 2005; Sinclair *et al.*, 2010) surface breaking cracks (Baskaran *et al.*, 2002) also discussed. Usage of ToFD in casting (Dukic and Dukic, 2000), fabricated pressure vessel components (Prabhakaran *et al.*, 2004) and to tackle the problems in sizing of defects inside pressure vessels & welded joints (Gabriel and Petru, 2004) also discussed. To identify echoes and get signals, the characteristics of transducers were proposed by Jennifer *et al.* (2006). Classification of weld defects using ToFD signals and PES were proposed by Silva *et al.* (2002), Veiga *et al.* (2005), C'Shekhar *et al.* (2006) and Lalithakumari *et al.* (2012). Usage of ToFD than that of NDT procedures was proposed by Charlesworth and Temple (2001). Using s-ToFD, Baskaran *et al.* (2006a) have found that the image defect very near to the scanning surface is improved by 20-35% than the traditional ToFD using longitudinal wave. They authors concluded that by using 5 MHz probe frequency and 40-50 of probe angles, the near-surface defects can be effectively inspected (Baskaran, 2006b). Mihara *et al.* (2004) found the advantage of absolute time measurement in laser ToFD method comparing to the conventional ToFD method. They measured the depth of slits in aluminum plates using developed laser ToFD system and estimated accuracy was within 3.6% for longitudinal wave measurement and within 5.9% for shear wave measurement. Tie and Dazhao (2008) found the buried depth and lateral location of a bottom surface broken crack tip within an error of 0.5 mm. ToFD technique has been used for automatic weld inspection. The usage of ToFD signals were proposed by C'Shekhar *et al.* (2006) and Silva *et al.* (2002) to classify the detected weld defects during inspection. The obtained ToFD A Scan data of defected austenitic stainless steel welds were used by Lalithakumari *et al.* (2012) to classify the weld defects. In this, the efficiency of defect detection is improved. The authors

(Muthumari *et al.*, 2011; Riahi *et al.*, 2006) concluded that ToFD has the most practical applicability in real time systems than that of any other NDT techniques. The usage of ToFD in casting inspection was proposed by Dukic and Dukic (2000). To achieve a reliability assessment of the ultrasonic technique for compounds with complex geometry by developing POD & POS using manual ToFD system was proposed by Nath *et al.* (2010). The authors (Riahi *et al.*, 2006) found that ToFD has been found to be more feasible to detect weld defects and thick layers of steel. Sinclair *et al.* (2010) proposed the sizing of defects by ToFD. The authors (Prabhakaran *et al.*, 2004) concluded that ToFD can be used to replace the traditional NDT methods of inspecting fabricated pressure vessel components. A signal processing technique based on EMD and the Hilbert transform to improve the time resolution of the ToFD signal, accurate sizing and location of deeper flaws was proposed by Sinclair *et al.* (2010) and Tianlu *et al.* (2005).

The authors (Veiga *et al.*, 2005) proposed the use of Artificial Neural Network in the classification of Pulse-Echo and ToFD Ultra-Sonic Signals from welds. And they concluded that ToFD has a reasonable rate of success 77.50 over 72.50% of pulse echo. The authors (Gabriel and Petru, 2004) tackled the problems in sizing of defects inside pressure vessels and welded joints using a common approach for ToFD and classical ultrasonic NDT. Applications of ToFD method for mechanical engineering for detection and dimensioning the discontinuities in the mechanical components were proposed by BOSSUAT *et al.* (2006). Using ToFD data, the task of automatic positioning and sizing of detected defects is proposed by Kechida *et al.* (2008). To inspect complex T-butt weld, the authors (Baskaran *et al.*, 2007) proposed ToFD technique using 2-D finite element method. The authors (Charlesworth and Temple, 2001) proposed the usage of ToFD to inspect materials than that of other NDT procedures. The authors (Zahran *et al.*, 2002) concluded that the processing techniques developed for GPR may be adapted for use with ToFD applications. In conventional method, 12.746 mm crack size has a maximum error of 0.245 mm. But (Yonghong *et al.*, 2008) have a maximum error of 0.048 mm for the same crack size using ToFD based on cross correlation method. Yuwen *et al.* (2010) proposed ToFD (B-scan ultrasonic image) based on edge detection to accurately detect the defects. ToFD imaging for double-probe reflection method is proposed by Young-Fo *et al.* (2002) to process the image and to detect the nonhorizontal flaws.

CONCLUSION

Conventional ToFD is limited to thick sections only i.e., thickness greater than 15 mm and thickness below 5 mm from the scanning surface. In it, near surface defects were overestimated. To improve accuracy, it requires scanning from both the surface of the specimen. In Near Surface Inspection, Detection and Sizing accuracy of longitudinal diffraction based technique is smaller than shear diffraction based measurements. To defeat the difficulties with inspection of thin sections and near surfaces using Conventional ToFD technique, s-ToFD is used. Even though diffraction coefficient of shear wave is less than the longitudinal wave, the use of shear diffracted wave is feasible in thin material. Even the longitudinal diffracted echo from the defect tip superimposes with the lateral wave (defects in thin and near surface), the shear diffracted echo from the defect is clearly separated. In Near Surface Inspection, Detection and Sizing accuracy of shear diffraction based measurements is greater than longitudinal diffraction based technique. Through s-ToFD, both the TOF measurements and the flaw sizing are to be improved. i-ToFD gives an interesting solution to detect the defect and identify the location of the defect in thin weldments.

ABBREVIATIONS

LF	: Lack of Fusion
LP	: Lack of Penetration
ART	: Acoustic Resonance Technology
EMAT	: Electro Magnetic Acoustic Transducer technology
LUT	: Laser Ultrasonics
IRIS	: Internal Rotary Inspection system (ultrasonics for tubes)
PA	: Phased Array
s-ToFD	: Shear wave ToFD
i-ToFD	: Immersion ToFD
UT	: Ultrasonic Testing
POD	: Probability of Detection

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